

Leptoquarks in FCNC charm decays

Svjetlana Fajfer^{1,2} and Nejc Košnik²

1) *Department of Physics, University of Ljubljana,
Jadranska 19, 1000 Ljubljana, Slovenia*

2) *J. Stefan Institute, Jamova 39, P. O. Box 300, 1001 Ljubljana*

ABSTRACT

Recently it was noticed that among many scenarios of new physics leptoquarks might compensate for the disagreement between the lattice and experimental results for the charmed strange meson decay constant. The leptoquarks might modify also the flavor changing neutral current charm decays. In this study we investigate impact of the scalar leptoquark with electric charge $-1/3$ on the dilepton invariant mass distribution in the $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay and on the branching ratios of the $D^0 \rightarrow \mu^+ \mu^-$ using the existing experimental results.

Recently, a discrepancy between the lattice results and experimental determination of f_{D_s} in leptonic $D_s \rightarrow \ell \nu_\ell$ was established [1]. It was suggested [1, 2] that leptoquarks might provide for the modification of the short distance part of the amplitude and account for the difference and at the same time, due to different helicity suppression, render the $D \rightarrow K \ell \nu_\ell$ branching ratio consistent with experiment. In [2] authors used the lattice-experiment discrepancy in f_{D_s} , measured branching ratio of semileptonic $D \rightarrow K \ell \nu_\ell$ and some additional assumptions about the mixing matrices of quarks and leptons to constrain the scalar leptoquark mediated flavor changing neutral currents, namely the $c \rightarrow u \ell^+ \ell^-$. This resulted in a leptoquark prediction of the $D \rightarrow \mu^+ \mu^-$ branching ratio which is close to current experimental sensitivity.

In this note, we study a possibility to probe the scalar leptoquark couplings in the $D^+ \rightarrow \pi^+ \ell^+ \ell^-$ decay. We will follow the approach of [3, 4], assuming the phenomenological Breit-Wigner ansatz for the long-distance resonant contributions, which by themselves generate branching ratio of around 2×10^{-6} . Motivated by the new experimental upper bound [5] on the branching ratio

$$\mathcal{B}(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 3.9 \times 10^{-6}, \quad (1)$$

we will find constraints on the scalar leptoquark mediated $c \rightarrow u \mu^+ \mu^-$ Lagrangian.

Lagrangian of the scalar \tilde{d} leptoquark in the $(3, 1, -1/3)$ representation of the Standard model

gauge group, coupled to the leptons and quarks is [1, 2]

$$\mathcal{L}_{LQ} = \tilde{d}_\alpha \kappa_\ell (\bar{\nu}_\ell P_R s_\alpha^c - \bar{\ell} P_R c_\alpha^c) + \tilde{d}_\alpha \kappa'_\ell \bar{\ell} P_L c_\alpha^c + \text{H.c.}, \quad (2)$$

where $\kappa^{(\prime)}$ denotes the effective coupling of second generation quarks to leptons $\kappa^{(\prime)} = (\kappa_e^{(\prime)}, \kappa_\mu^{(\prime)}, \kappa_\tau^{(\prime)})^T$, $q^c = i\gamma_2 q^*$ are the charge-conjugated quarks, $P_{L,R} = (1 \mp \gamma_5)/2$, and α denotes the color index. This model aims at the resolution of the puzzle in $D_s \rightarrow \ell \nu_\ell$ and in order not to destroy the consistency between lattice and experiment in $D_d \rightarrow \ell \nu_\ell$, it only couples to quarks of the second generation. For constraints on the first quark generation, see [6, 7]. The Lagrangian given in (2) is valid for the quark and lepton states given in the weak basis. Noticing that the Cabibbo-Kobayashi-Maskawa matrix is made of the matrices which diagonalize up and down quarks' mass matrices $V_{CKM} = A_L^{(u)} A_L^{(d)\dagger}$ and Pontecorvo-Maki-Nakagawa-Sakata matrix is made of $U_{PMNS} = A_L^{(\nu)} A_L^{(\ell)\dagger}$, which diagonalize neutrino and lepton mass matrices, we derived, using Fierz identities, the following effective Lagrangian for the $c \rightarrow u \ell^+ \ell^-$ transition.

$$\begin{aligned} \mathcal{L}_{\text{eff}}(c \rightarrow u \ell^+ \ell^-) = \frac{1}{8M_{\tilde{d}}^2} & \left[C_{\ell c}^{L*} C_{\ell u}^L (\bar{u}c)_{V-A} (\bar{\ell}\ell)_{V-A} + C_{\ell c}^{R*} C_{\ell u}^R (\bar{u}c)_{V+A} (\bar{\ell}\ell)_{V+A} \right. \\ & + C_{\ell c}^{L*} C_{\ell u}^R \left(\frac{1}{2} (\bar{u}\sigma^{\mu\nu}c) (\bar{\ell}\sigma_{\mu\nu}(1 - \gamma_5)\ell) - (\bar{u}c)_{S-P} (\bar{\ell}\ell)_{S-P} \right) \\ & \left. + C_{\ell c}^{R*} C_{\ell u}^L \left(\frac{1}{2} (\bar{u}\sigma^{\mu\nu}c) (\bar{\ell}\sigma_{\mu\nu}(1 + \gamma_5)\ell) - (\bar{u}c)_{S+P} (\bar{\ell}\ell)_{S+P} \right) \right] \quad (3) \end{aligned}$$

In the above expression, effective coupling constants are products of leptoquark couplings $\kappa^{(\prime)}$ and fermion mixing matrices:

$$C^L \equiv A_L^{(\ell)} \kappa(A_R^{(u)\dagger})_2, \quad (4a)$$

$$C^R \equiv A_R^{(\ell)} \kappa'(A_L^{(u)\dagger})_2, \quad (4b)$$

with $(A_{(R,L)}^{(u)\dagger})_2$ being the second row of the matrix $A_{(R,L)}^{(u)\dagger}$, and $M_{\tilde{d}}$ is the mass of the leptoquark. In our calculations we do not use additional assumption on the quark and lepton mixing matrices as it was done in [2]. Instead we use the abovementioned general parameterization. As noted in [2], tensor terms do not contribute to the dileptonic decay $D \rightarrow \ell^+ \ell^-$, while terms of the type $(V \pm A) \otimes (V \pm A)$ are helicity suppressed by a factor of m_ℓ . However, in the $D^+ \rightarrow \pi^+ \ell^+ \ell^-$ also terms with tensors contribute without helicity suppression. We use the lattice determined hadronic form factors of the $D^+ \rightarrow \pi^+$ transition [8]. For the tensor form factor, we use the formula, valid in the heavy-quark limit $s(q^2) = F_1(q^2)/m_D$ [3].

In the long-distance amplitude we account for the 1^- resonances using the phenomenological

Breit-Wigner form (for more details see [3, 4]).

$$\mathcal{A}^{\text{LD}} = \left[a_\rho \left(\frac{1}{q^2 - m_\rho^2 + im_\rho \Gamma_\rho} - \frac{1}{3} \frac{1}{q^2 - m_\omega^2 + im_\omega \Gamma_\omega} \right) - \frac{a_\phi}{q^2 - m_\phi^2 + im_\phi \Gamma_\phi} \right] \bar{u}(k_-) \not{p} v(k_+) \quad (5)$$

Procedure of fitting of the long-distance amplitude to the updated experimental data [9] is described in [3] and we find

$$a_\rho = (2.5 \pm 0.2) \times 10^{-9}, \quad (6a)$$

$$a_\phi = (4.1 \pm 0.2) \times 10^{-9}. \quad (6b)$$

Errors in (6) are related to experimental errors of $\mathcal{B}(D^+ \rightarrow \pi^+ \rho)$ and $\mathcal{B}(D^+ \rightarrow \pi^+ \phi)$. The total differential decay width is a sum of long-distance and leptoquark contributions, where the former dominates the width in resonant part of the spectrum and the latter elsewhere. This observation allows us to neglect the interference term between the long-distance and leptoquark contributions, as it must be unimportant for the total decay width (see Fig. 1). The long-distance term generates partial branching ratio of $(1.8 \pm 0.2) \times 10^{-6}$, where the uncertainty stems from the errors in (6). In the conservative manner, we will set the long-distance branching ratio to the minimal allowed value of 1.6×10^{-6} and saturate the remaining 2.3×10^{-6} to the measured branching ratio (1) with leptoquark contribution. In our study we neglect the mass of the muon, which removes dependence on the phases of couplings $C^{L,R}$, and arrive at the following condition.

$$6.07 \times 10^{-5} \frac{|C_{\mu c}^L C_{\mu u}^L|^2 + |C_{\mu c}^R C_{\mu u}^R|^2}{(M_{\tilde{d}}/\text{TeV})^4} + 9.15 \times 10^{-5} \frac{|C_{\mu c}^L C_{\mu u}^R|^2 + |C_{\mu c}^R C_{\mu u}^L|^2}{(M_{\tilde{d}}/\text{TeV})^4} = 2.3 \times 10^{-6} \quad (7)$$

From (7) follow the bounds on two distinct combinations of the leptoquark couplings from the $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ branching ratio.

$$\frac{|C_{\mu c}^{L(R)} C_{\mu u}^{L(R)}|}{(M_{\tilde{d}}/\text{TeV})^2} < 0.19, \quad \frac{|C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}|}{(M_{\tilde{d}}/\text{TeV})^2} < 0.16 \quad (8)$$

Decay spectra, which saturate (1), are shown on Fig. 1 with dashed lines, where we show the maximal contribution of $C_{\mu c}^{L(R)} C_{\mu u}^{L(R)}$ and $C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}$ separately. The former contribution is proportional to the $F_1(q^2)$ form factor, while the latter is proportional to the combination of tensor $s(q^2)$ and $F_0(q^2)$ form factor and also to q^2 . The latter couplings are present also in the bileptonic decay $D^0 \rightarrow \mu^+ \mu^-$, for which the branching ratio (with m_μ again set to zero and f_D taken from [10]) is

$$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) = \tau_{D^0} \frac{f_D^2 m_{D^0}^5}{256 \pi m_c^2} \frac{|C_{\mu c}^L C_{\mu u}^R|^2 + |C_{\mu c}^R C_{\mu u}^L|^2}{M_{\tilde{d}}^4}. \quad (9)$$

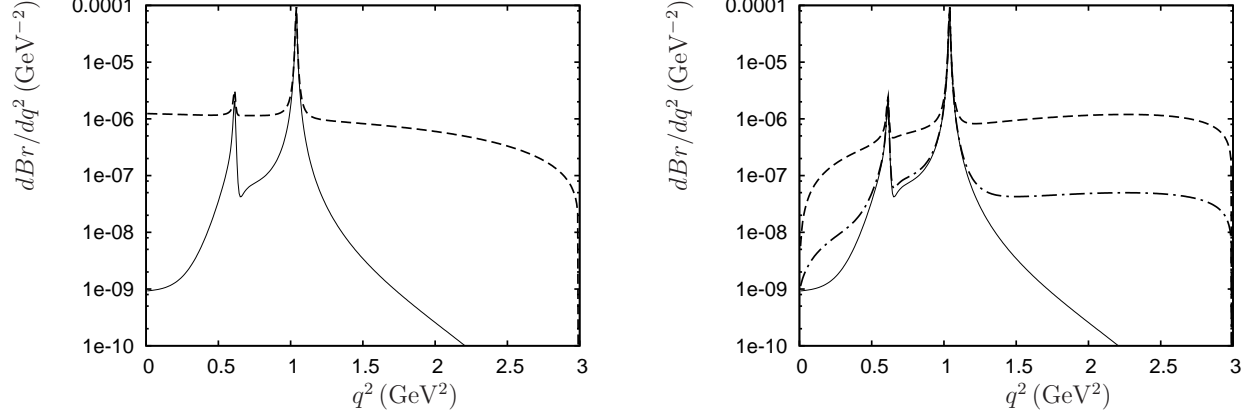


Figure 1: Spectra of $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay. Left: Dashed line shows saturation of (1) with the $C_{\mu c}^{L(R)} C_{\mu u}^{L(R)}$. Right: Dashed line shows saturation of (1) with the $C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}$, while the dash-dotted line is the same couplings' contribution, but bounded from $D^0 \rightarrow \mu^+ \mu^-$. Both graphs: Full line is the long-distance spectrum.

From experimental result $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 5.3 \times 10^{-7}$ [11] we obtain the bound

$$\frac{|C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}|}{(M_{\tilde{d}}/\text{TeV})^2} < 0.032, \quad (10)$$

which is 1 order of magnitude more severe than the bound from $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ (8). From (10) we predict the maximal contribution of $C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}$ to $\mathcal{B}(D^+ \rightarrow \pi^+ \mu^+ \mu^-)$ to be 9.4×10^{-8} (Fig. 1, dash-dotted line) which is almost impossible to detect due to the resonant branching ratio pollution of $(1.8 \pm 0.2) \times 10^{-6}$. However, the $C_{\mu c}^{L(R)} C_{\mu u}^{L(R)}$ can only be probed by measuring the spectrum of $D^+ \rightarrow \pi^+ \mu^+ \mu^-$, where an enhancement of about 3 orders of magnitude with respect to the resonant amplitude is expected at low q^2 (dashed line in Fig.1, left).

We estimated the scalar $Q = -1/3$ leptoquark contribution to $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ and $D^0 \rightarrow \mu^+ \mu^-$ branching ratios. The 3-body decay mode is sensitive to both $C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}$ and $C_{\mu c}^{L(R)} C_{\mu u}^{L(R)}$, and we have shown that with additional input from the dileptonic decay, one can use the measured branching ratio of $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ to probe directly the leptoquark couplings that are otherwise inaccessible to $D^0 \rightarrow \mu^+ \mu^-$. Further experimental study of $D^+ \rightarrow \pi^+ \mu^+ \mu^-$, especially in the low q^2 region, together with improving measurements of $D^0 \rightarrow \ell^+ \ell^-$, $D \rightarrow K \nu \ell$ and $D^0 - \bar{D}^0$ mixing [12] can help decide whether leptoquarks can solve the f_{D_s} puzzle.

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